US007847732B1

(12) **United States Patent**
Nabar et al.

(10) **Patent No.: US 7,847,732 B1**
(45) **Date of Patent: *Dec. 7, 2010**

(54) **STEERING MATRIX FEEDBACK FOR BEAMFORMING**

(75) Inventors: **Rohit Nabar**, Sunnyvale, CA (US); **Hui-Ling Lou**, Palo Alto, CA (US); **Peter Loc**, Cupertino, CA (US)

(73) Assignee: **Marvell International Ltd.**, Hamilton (BM)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **12/535,349**

(22) Filed: **Aug. 4, 2009**

Related U.S. Application Data

(63) Continuation of application No. 11/481,142, filed on Jul. 5, 2006, now Pat. No. 7,570,210.

(60) Provisional application No. 60/749,550, filed on Dec. 12, 2005.

(51) **Int. Cl.**
H01Q 3/00 (2006.01)

(52) **U.S. Cl.** **342/373**

(58) **Field of Classification Search** 342/373, 342/377

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,061,023	A	5/2000	Daniel et al.	
7,151,809	B2	12/2006	Ketchum et al.	
2007/0042717	A1*	2/2007	Alexiou et al.	455/69
2007/0129018	A1	6/2007	Trainin et al.	
2008/0069015	A1*	3/2008	Walton et al.	370/280

FOREIGN PATENT DOCUMENTS

WO WO 01/93456 A1 12/2001

OTHER PUBLICATIONS

Haynes, Toby; "A Primer on Digital Beamforming"; http://www.spectrumsignal.com/ Mar. 28, 1998;15 pages.

HT PHY Specification; Enhanced Wireless Consortium publication; V1.27; Dec. 23, 2005; 67 pages.

HT MAC Specification; Enhanced Wireless Consortium publication; V1.24; 2005; 100 pages.

Banister et al., "Feedback Assited Stochastic Gradient Adaptation of Mulitantenna Transmission." IEEE Transactions on Wireless Commuications vol. 4, No .3 (May 1, 2005): pp. 1121-1135. Abstract.: p. 1122, paragraph II.A—p. 1124, paragraph II.A.

Notification of Transmittal of The International Search Report and The Written Opinion of The International Searching Authority, or The Declaration dated Sep. 16, 2009 in reference to PCT/IB2009/005099 (15 pgs).

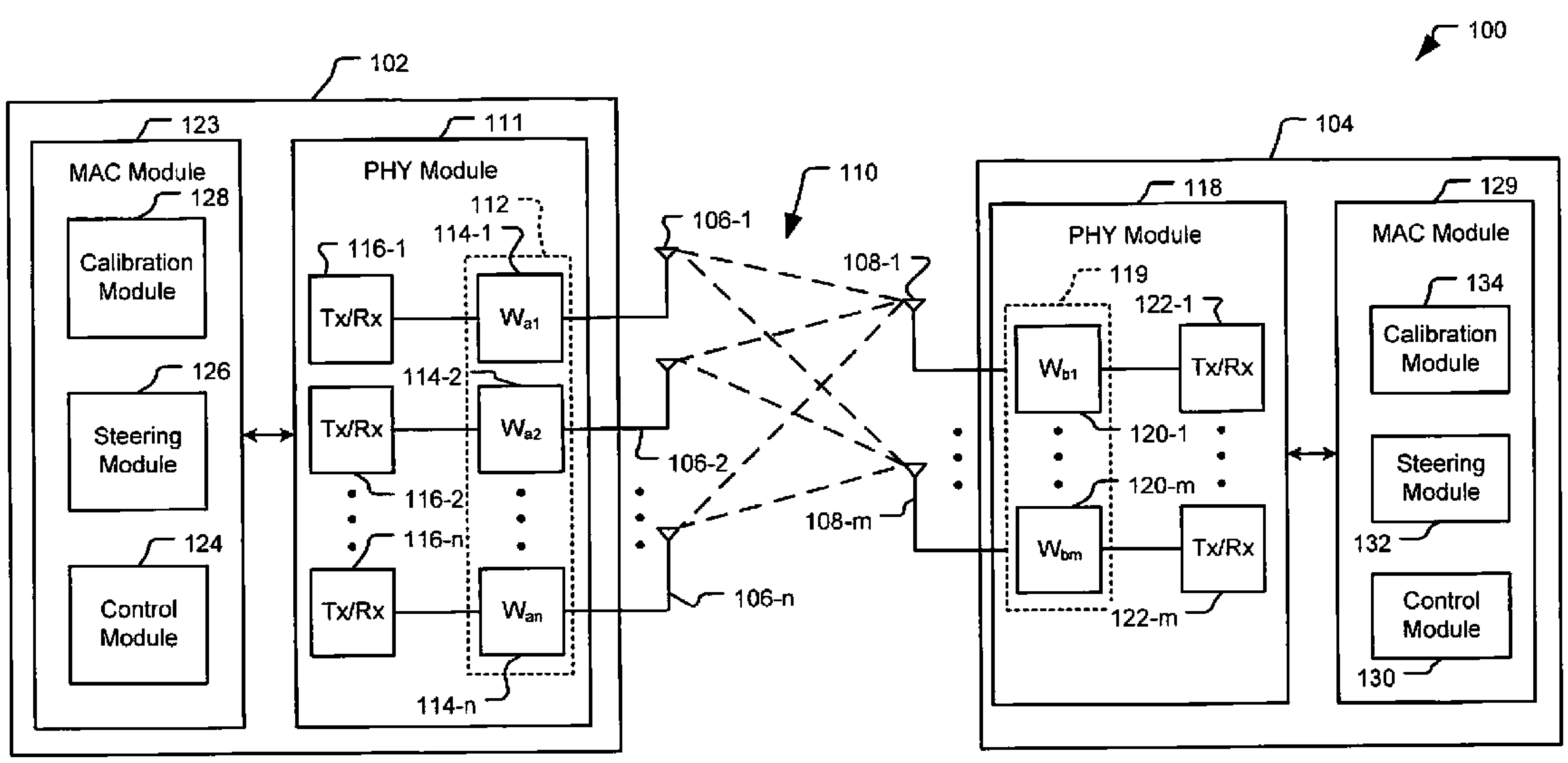
* cited by examiner

Primary Examiner—Thomas H Tarcza
Assistant Examiner—Nga X Nguyen

(57) **ABSTRACT**

A first network device includes a calibration module configured to receive a training signal from a second network device. The training signal indicates the second network device is capable of adjusting beamforming weights associated with the second network device based on a steering matrix received from the first network device. A steering module is configured to determine a first steering matrix for the second network device based on the training signal. The steering module is configured to transmit the first steering matrix to the second network device for adjustment of the beamforming weights associated with the second network device.

13 Claims, 11 Drawing Sheets



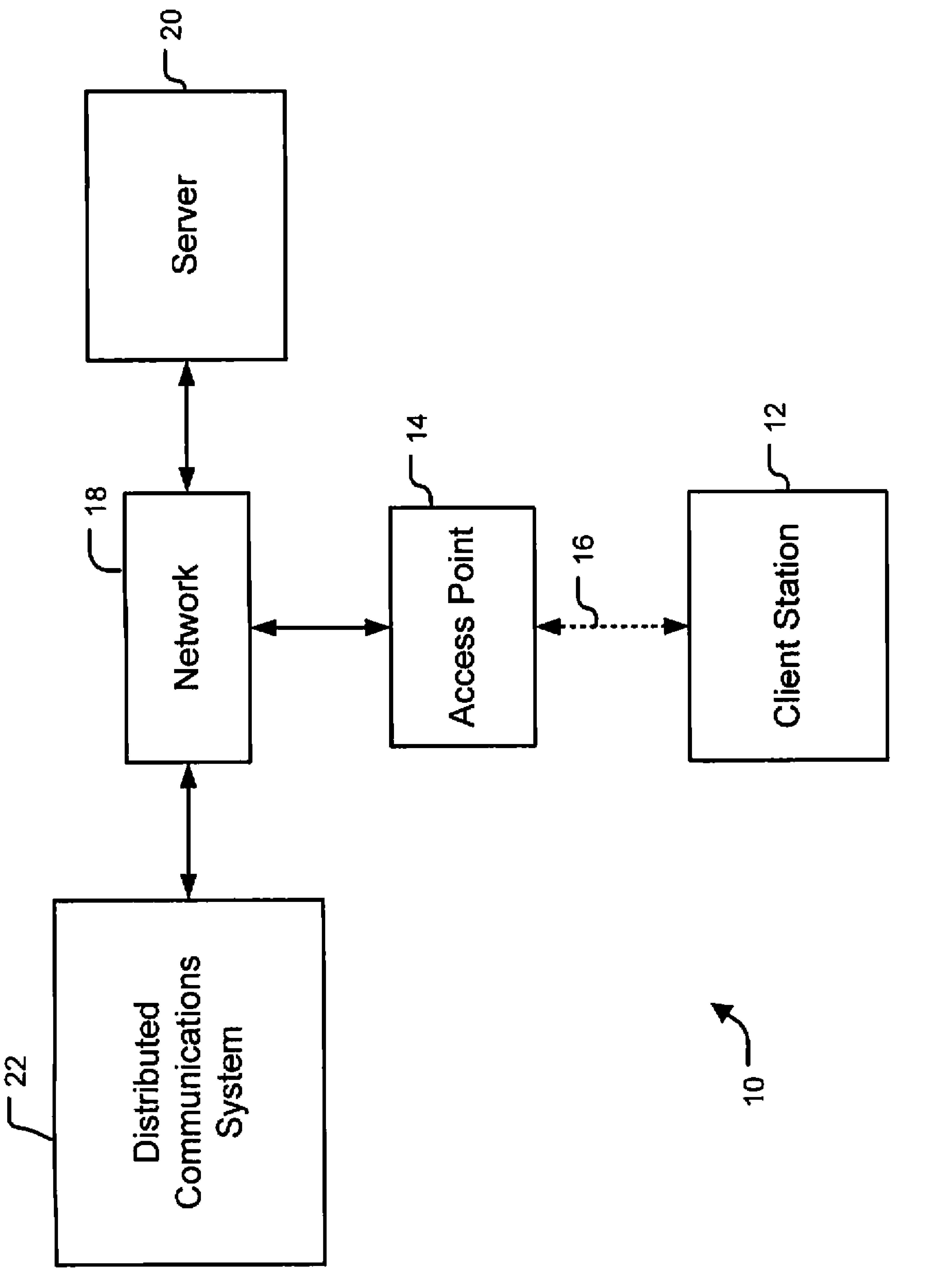


FIG. 1
Prior Art

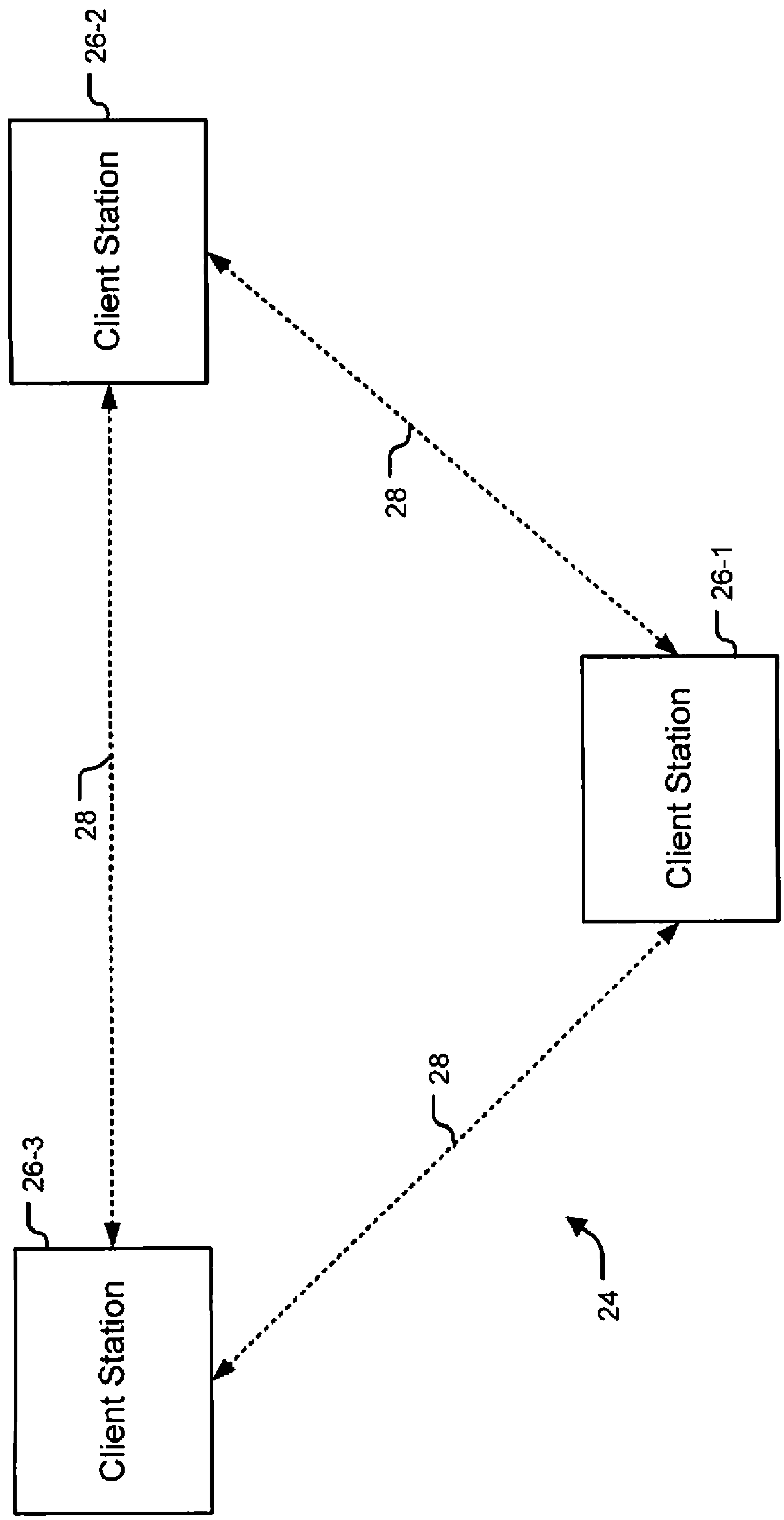


FIG. 2
Prior Art

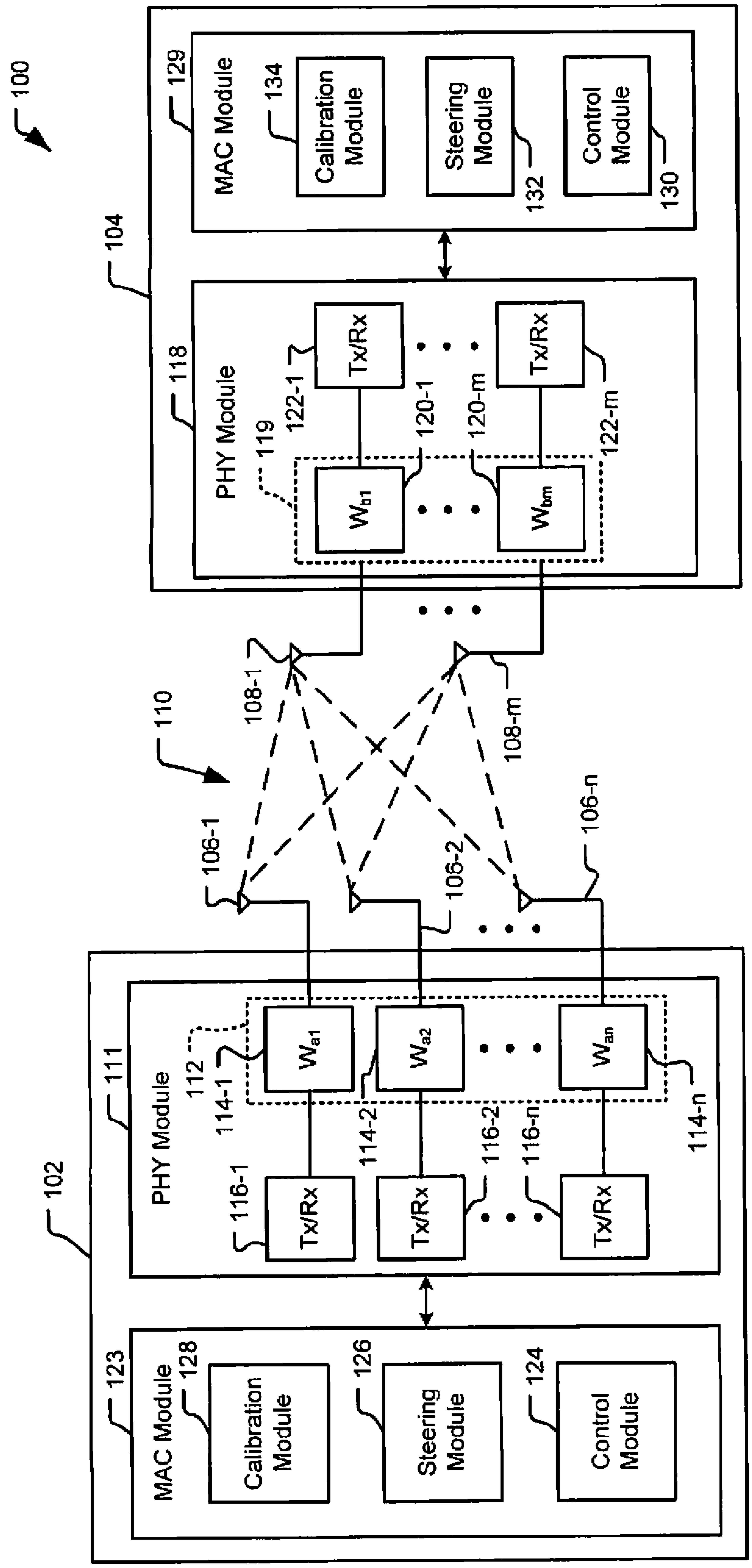

100
104
MAC Module
129
Calibration Module
134
Steering Module
132
Control Module
130
PHY Module
118
119
Tx/Rx
122-1
120-1
Tx/Rx
120-m
122-m
W_{b1}
W_{bm}
108-1
108-m
110
106-1
106-2
106-n
102
PHY Module
111
112
114-1
W_{a1}
W_{a2}
W_{an}
114-2
116-2
116-n
114-n
116-1
Tx/Rx
Tx/Rx
Tx/Rx
MAC Module
123
128
Calibration Module
126
Steering Module
124
Control Module

FIG. 3

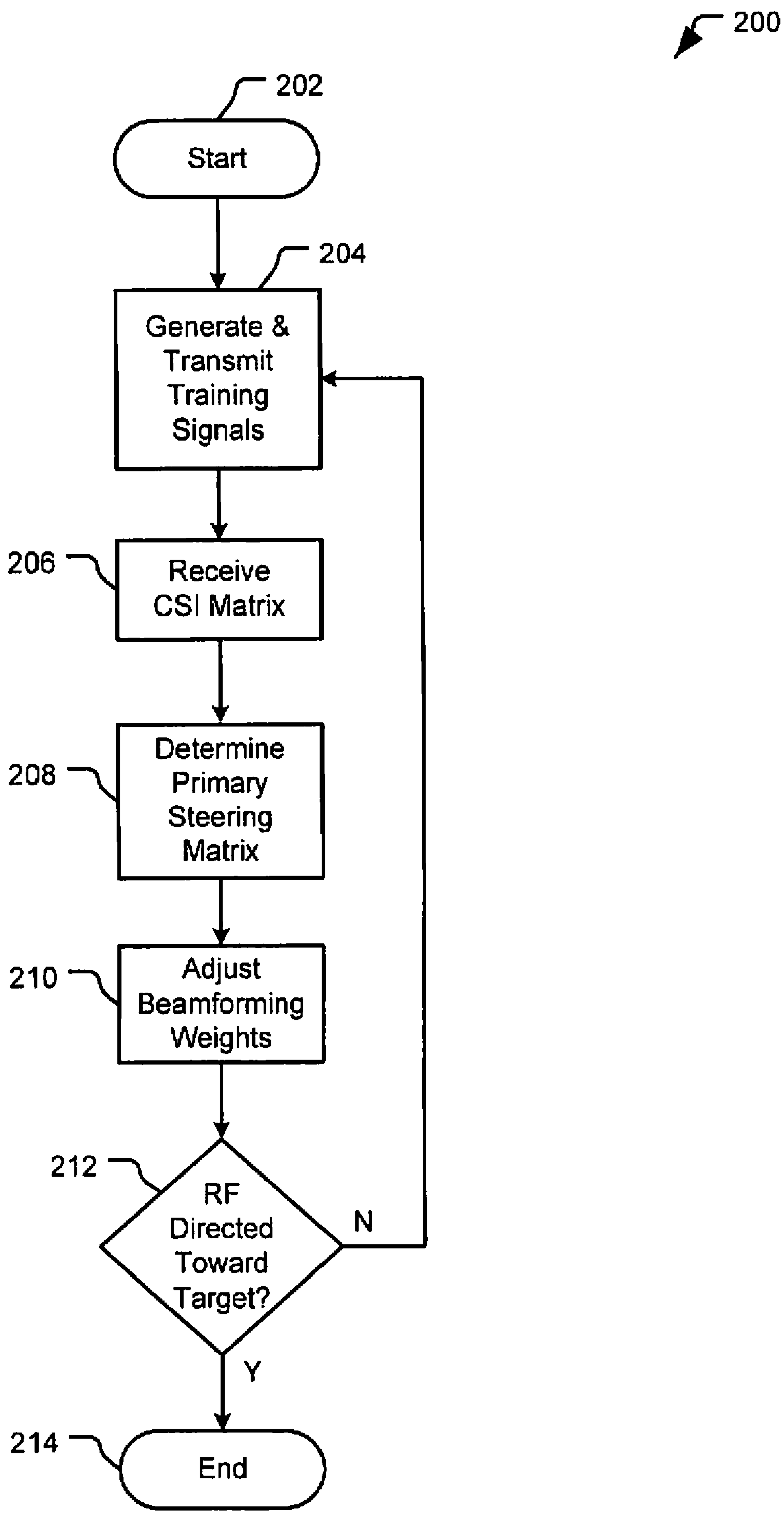

200
202
Start
204
Generate & Transmit Training Signals
206
Receive CSI Matrix
208
Determine Primary Steering Matrix
210
Adjust Beamforming Weights
212
RF Directed Toward Target?
N
Y
214
End

FIG. 4

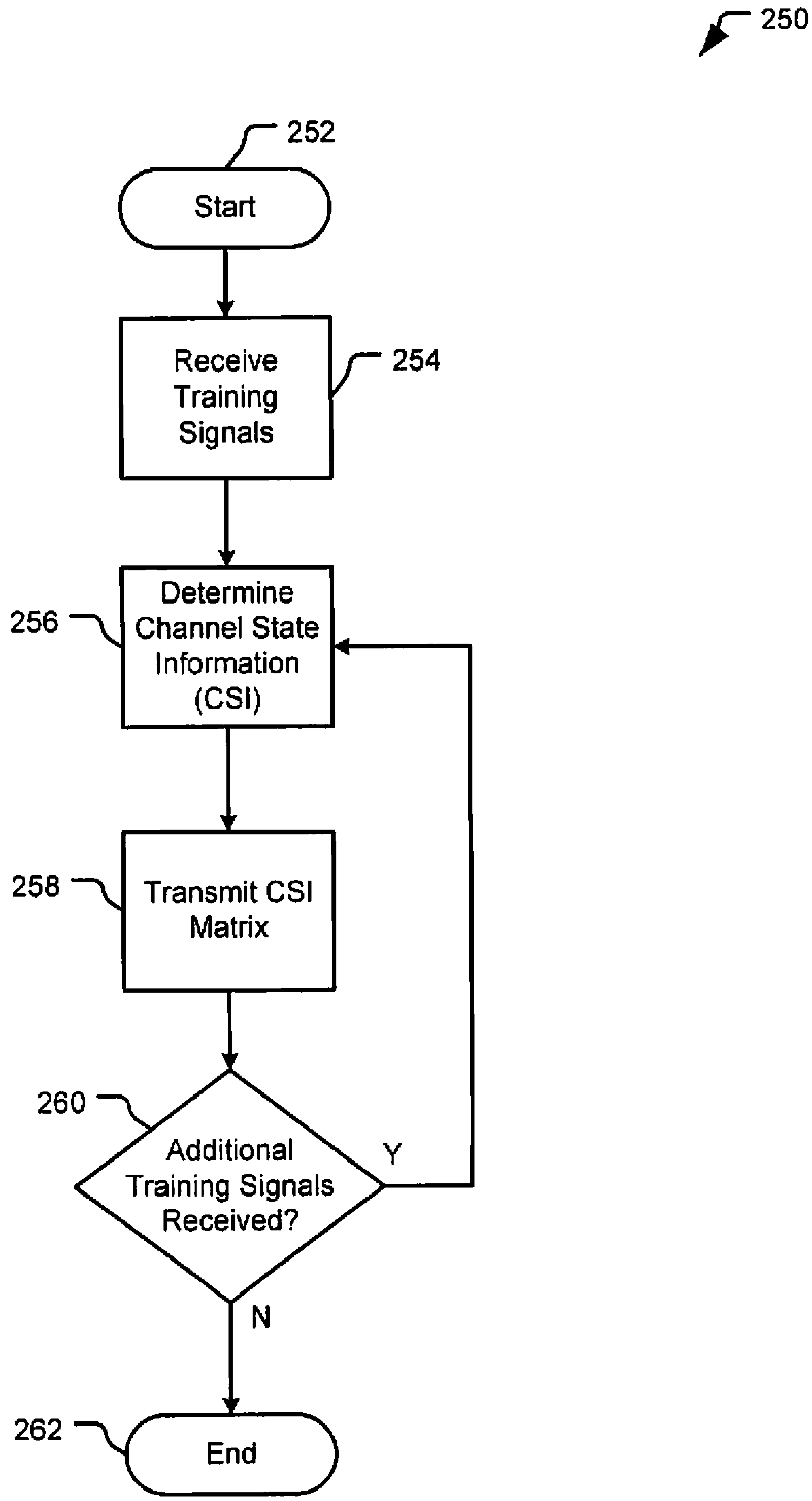

250
252
Start
Receive Training Signals
254
256
Determine Channel State Information (CSI)
258
Transmit CSI Matrix
260
Additional Training Signals Received?
Y
N
262
End

FIG. 5

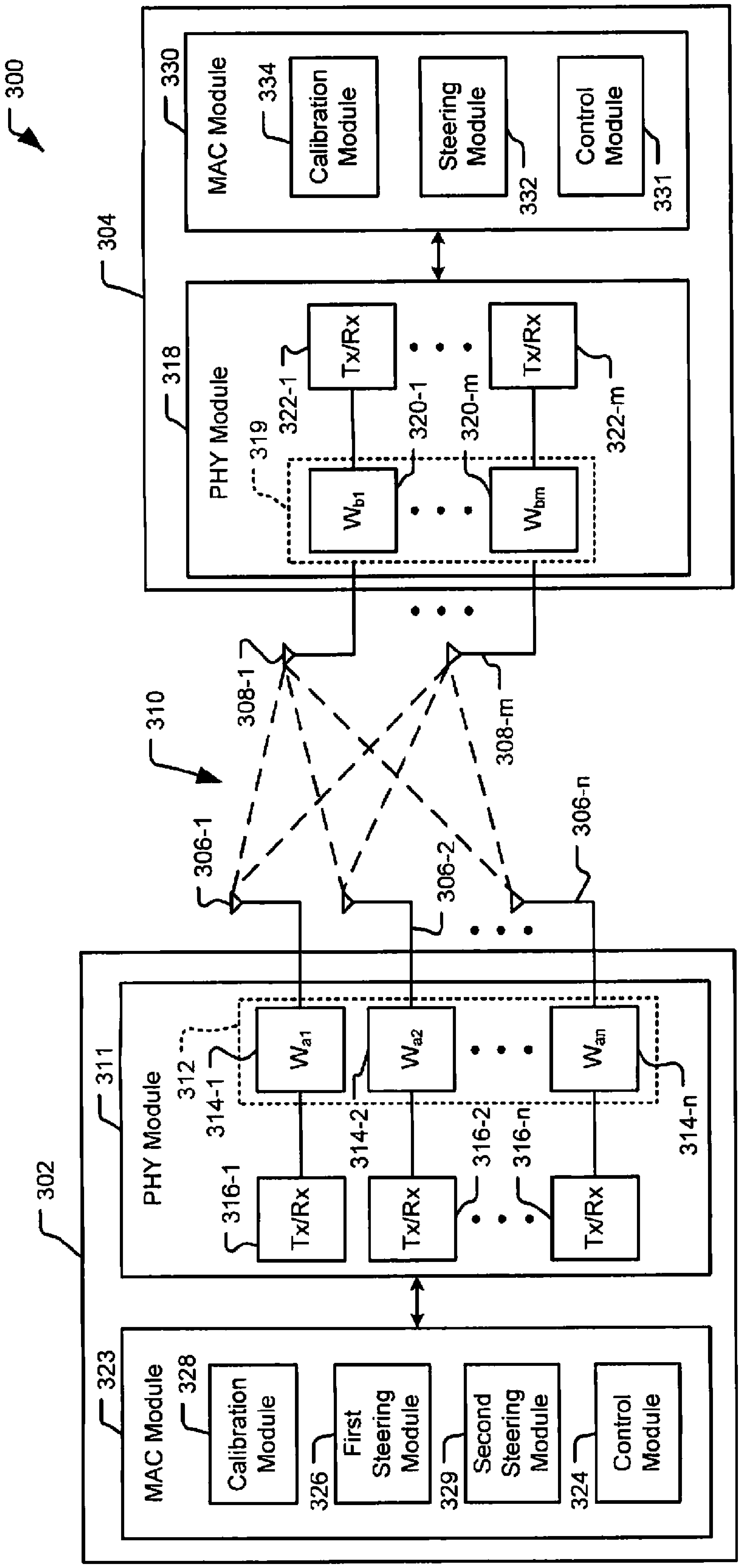

300
304
330
MAC Module
334
Calibration Module
Steering Module
332
Control Module
331
318
PHY Module
319
322-1
Tx/Rx
320-1
320-m
Tx/Rx
322-m
W_{b1}
W_{bm}
308-1
308-m
310
306-1
306-2
306-n
302
311
PHY Module
312
314-1
W_{a1}
W_{a2}
W_{an}
314-2
316-2
316-n
314-n
316-1
Tx/Rx
Tx/Rx
Tx/Rx
323
MAC Module
328
Calibration Module
326
First Steering Module
329
Second Steering Module
324
Control Module

FIG. 6

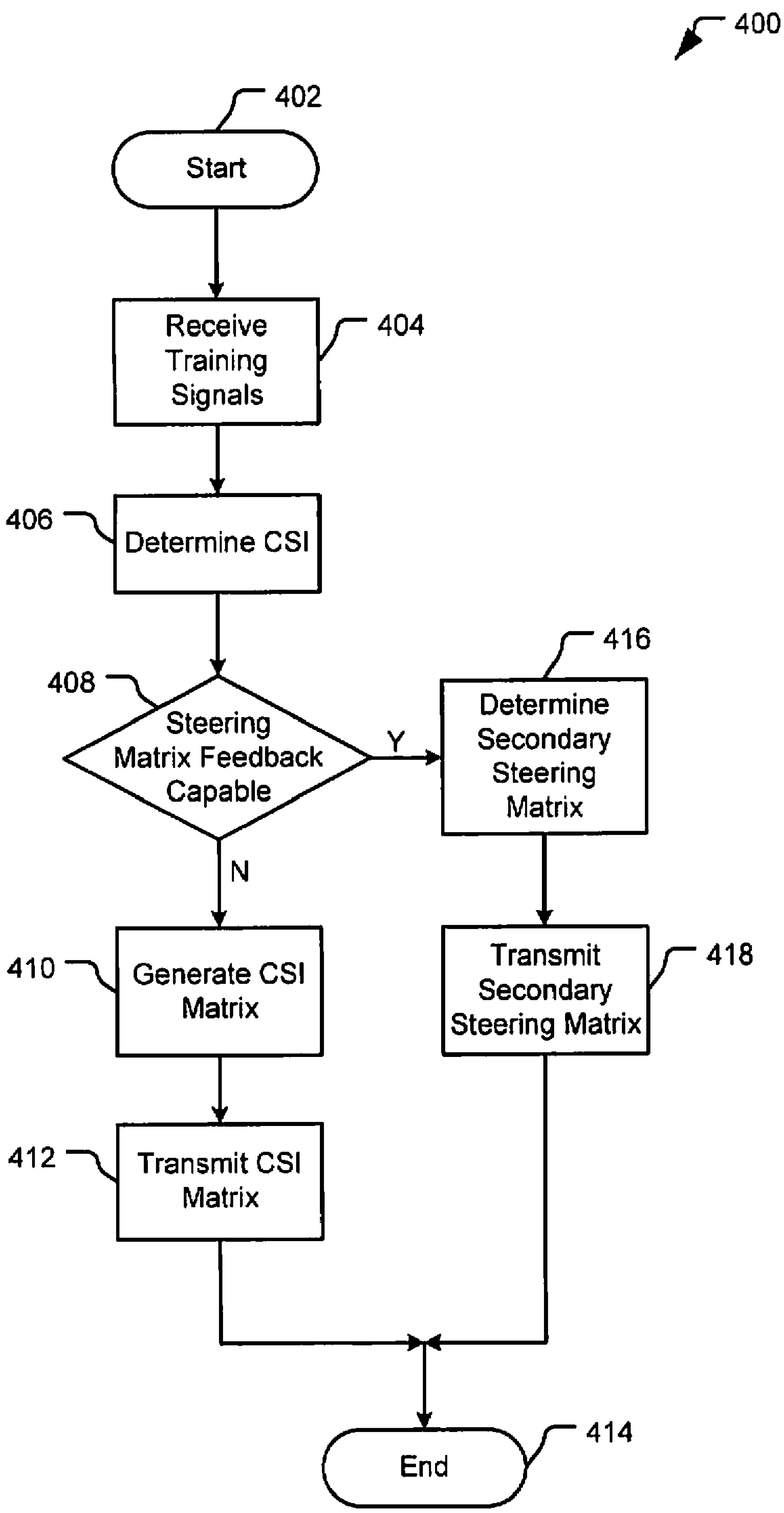

400
402
Start
Receive Training Signals
404
406
Determine CSI
408
Steering Matrix Feedback Capable
Y
416
Determine Secondary Steering Matrix
N
410
Generate CSI Matrix
Transmit Secondary Steering Matrix
418
412
Transmit CSI Matrix
End
414

FIG. 7

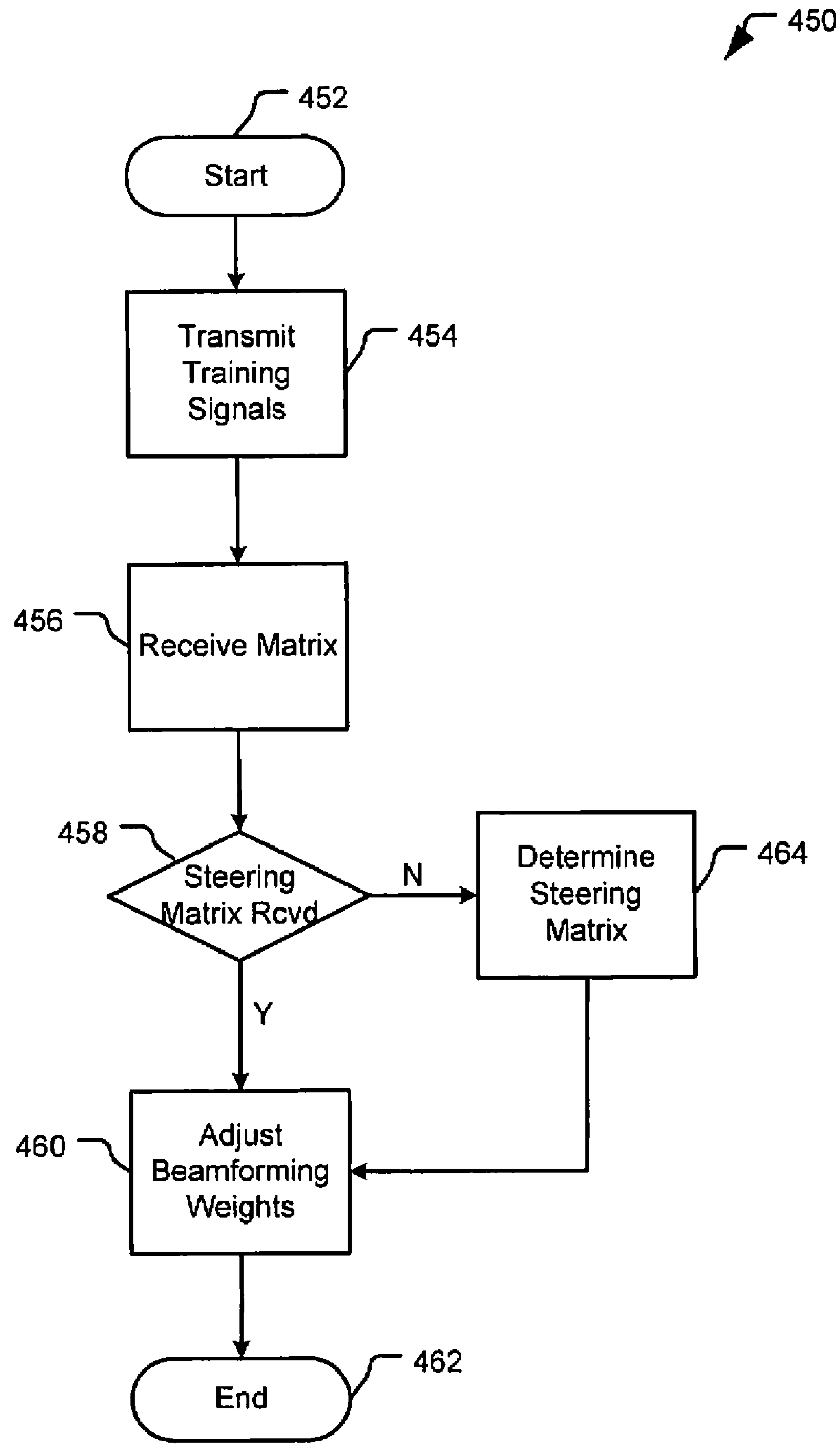

450
452
Start
Transmit Training Signals
454
456
Receive Matrix
458
Steering Matrix Rcvd
N
Determine Steering Matrix
464
Y
460
Adjust Beamforming Weights
End
462

FIG. 8

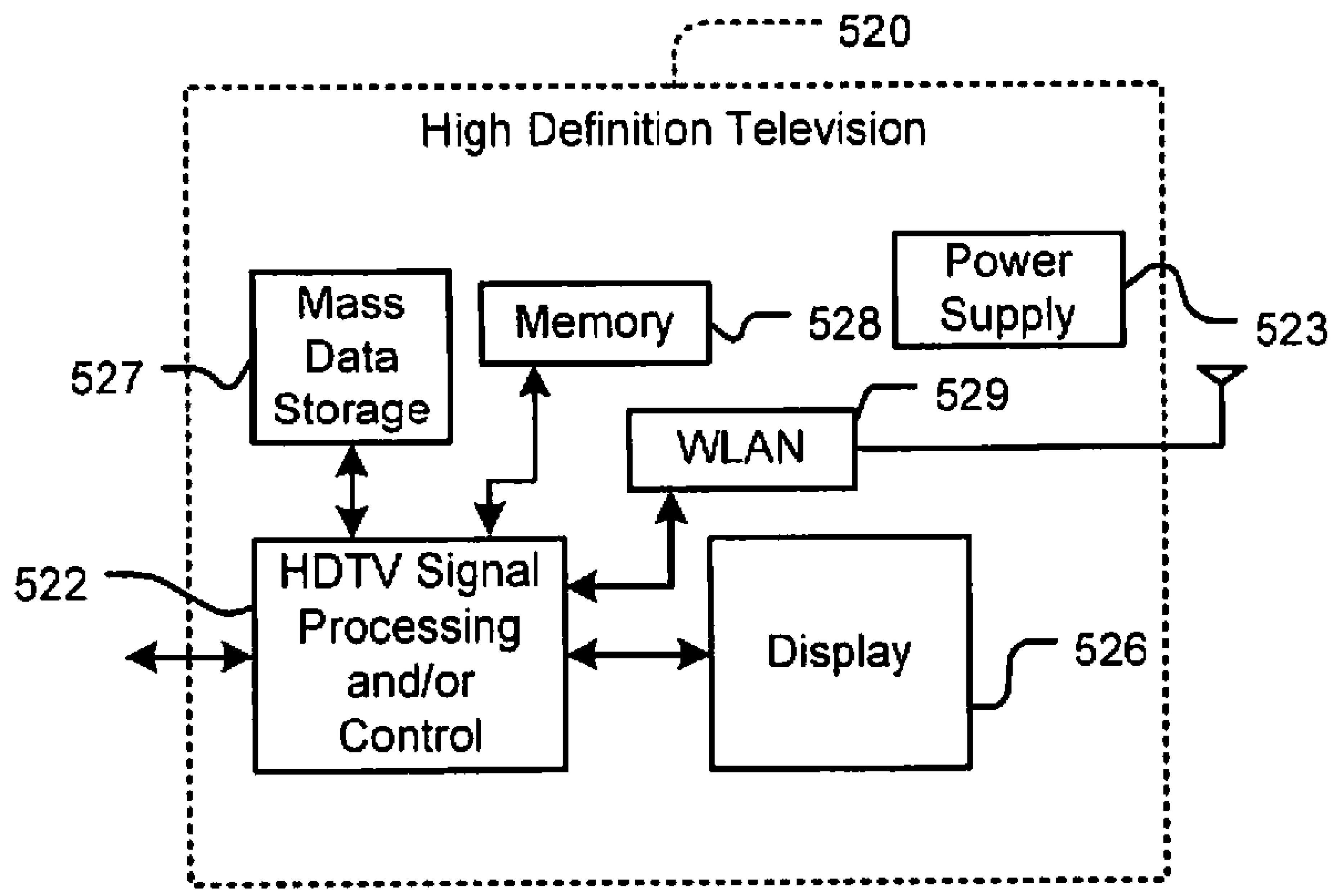

520
High Definition Television
Mass Data Storage
Memory
528
Power Supply
523
527
WLAN
529
522
HDTV Signal Processing and/or Control
Display
526

FIG. 9A

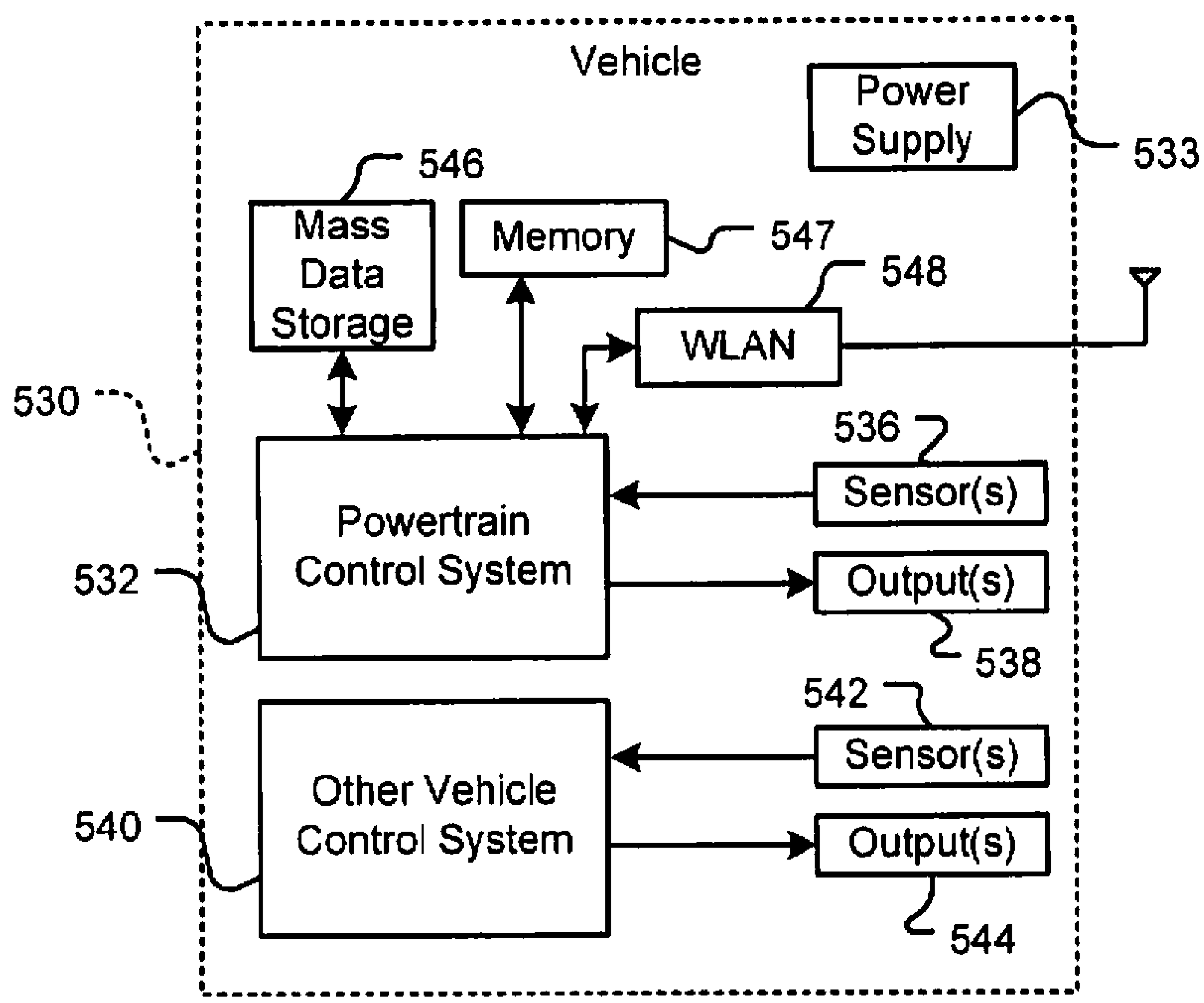

Vehicle
Power Supply
533
546
Mass Data Storage
Memory
547
548
WLAN
530
536
Sensor(s)
Powertrain Control System
532
Output(s)
538
542
Sensor(s)
Other Vehicle Control System
540
Output(s)
544

FIG. 9B

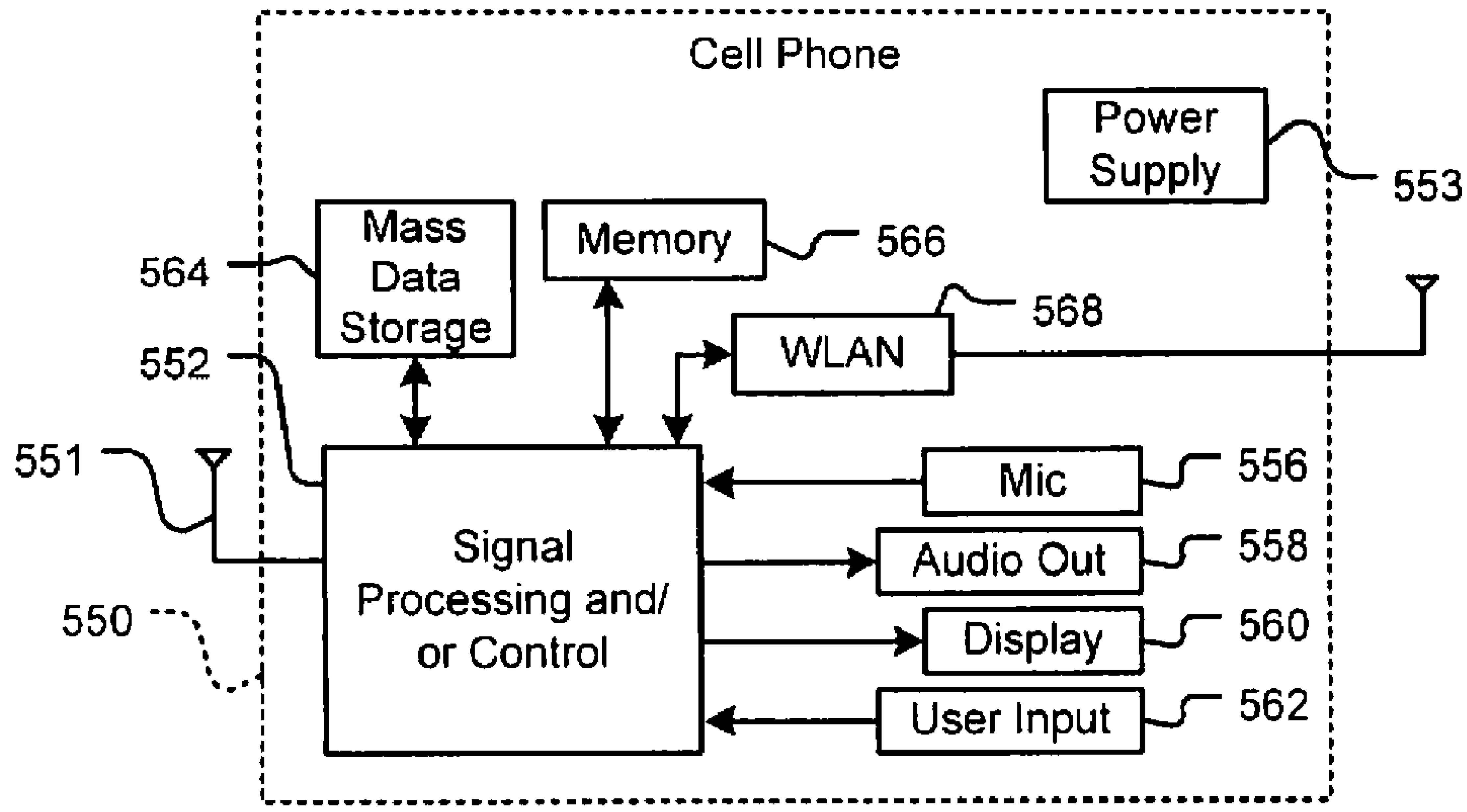

Cell Phone
Power Supply
553
Mass Data Storage
Memory
566
564
568
WLAN
552
551
Signal Processing and/ or Control
Mic
556
Audio Out
558
Display
560
550
User Input
562

FIG. 9C

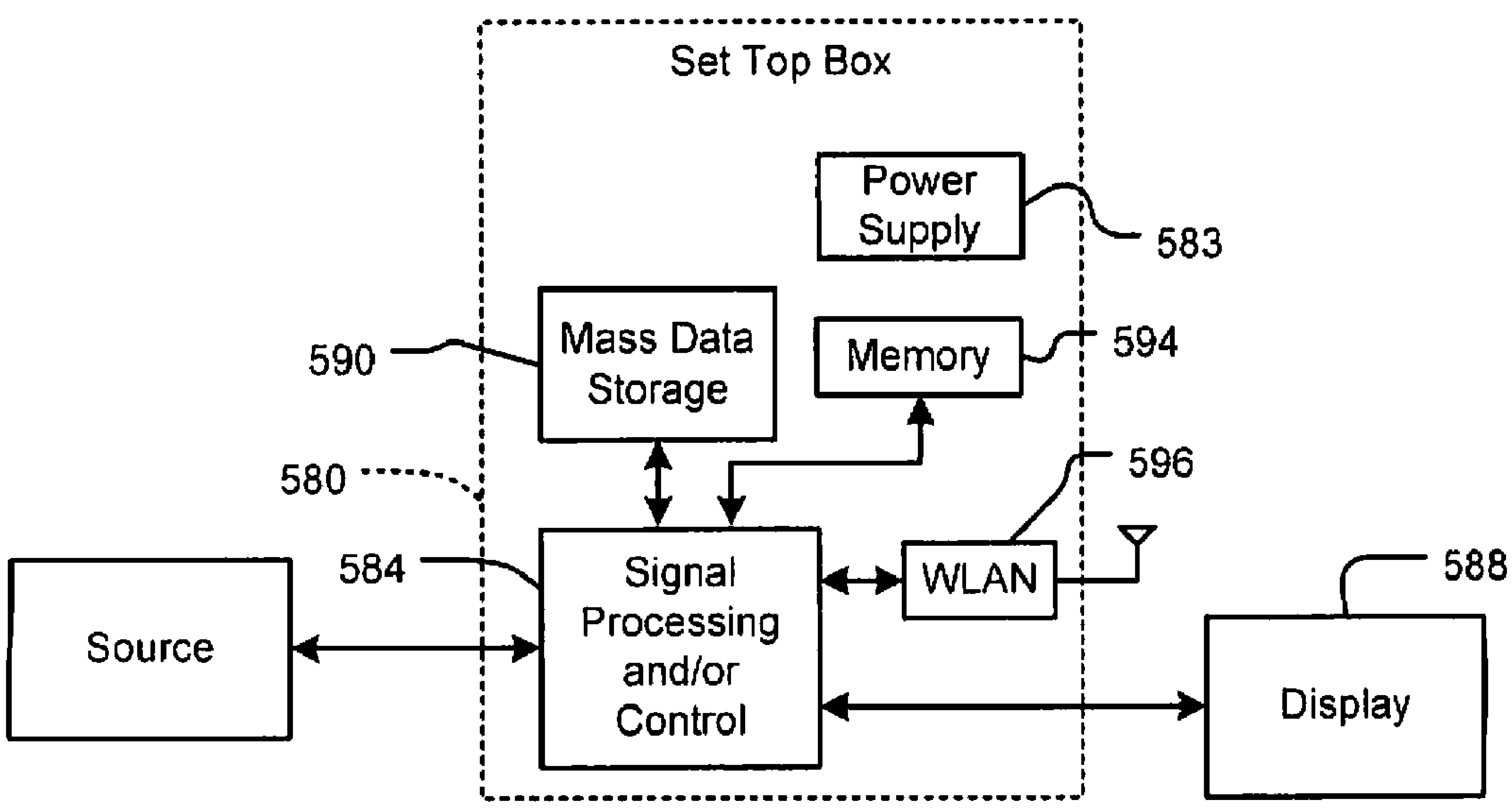

Set Top Box
Power Supply
583
590
Mass Data Storage
Memory
594
580
596
584
Signal Processing and/or Control
WLAN
588
Source
Display

FIG. 9D

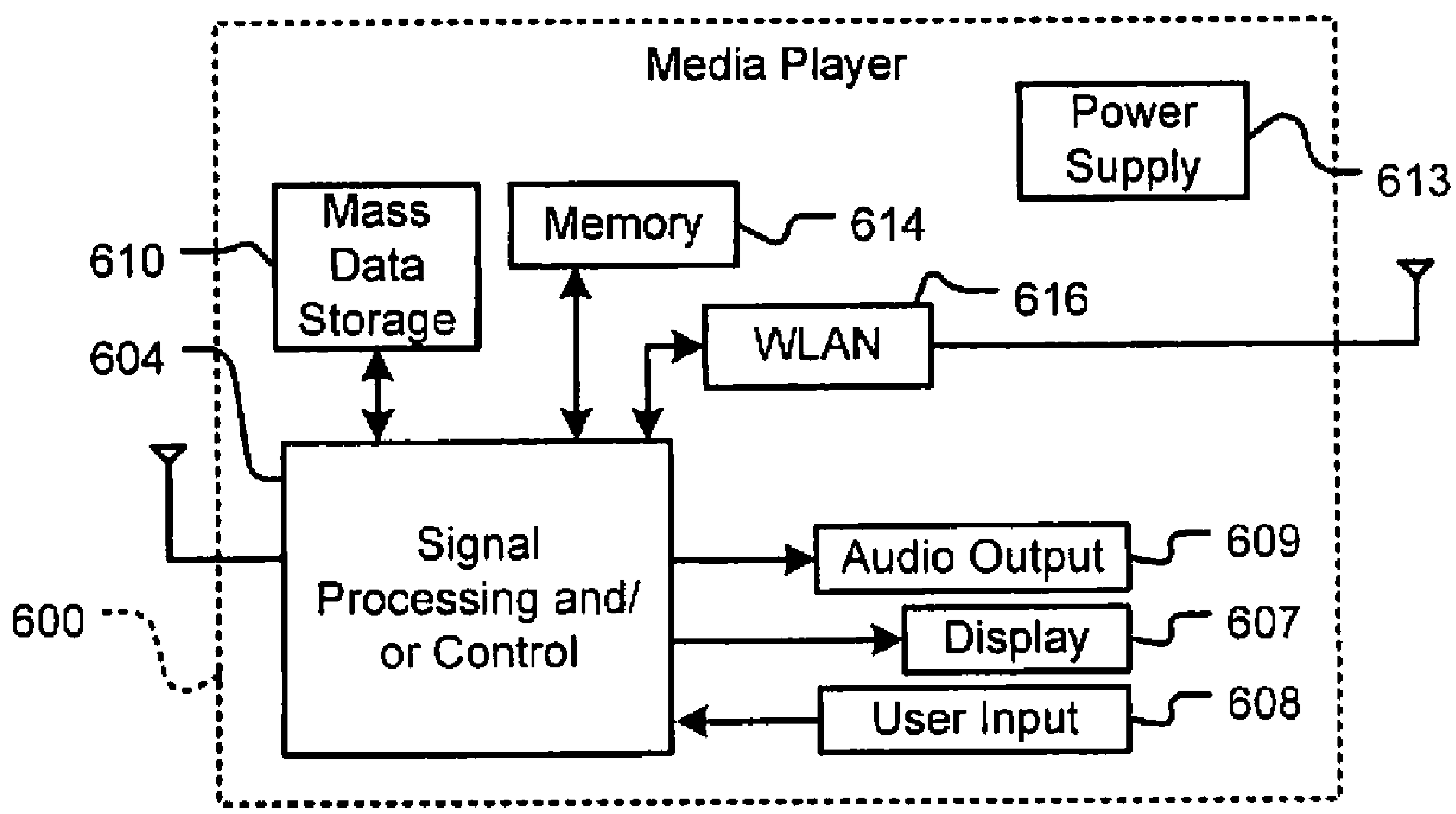

Media Player
Power Supply
613
Mass Data Storage
Memory
614
610
616
WLAN
604
Signal Processing and/or Control
Audio Output
609
600
Display
607
User Input
608

FIG. 9E

STEERING MATRIX FEEDBACK FOR BEAMFORMING

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 11/481,142, filed Jul. 5, 2006, which claims the benefit of U.S. Provisional Application No. 60/749,550, filed Dec. 12, 2005. The disclosures of the above applications are incorporated herein by reference in their entirety.

FIELD

The present disclosure relates to wireless network devices, and more particularly to directing radio frequency signals toward a particular target.

BACKGROUND

IEEE defined several different standards for configuring wireless networks and devices. The wireless network devices may be operated in either an infrastructure mode or an ad-hoc mode. In the infrastructure mode, the wireless network devices or client stations communicate with each other through an access point. In the ad-hoc mode, the wireless network devices communicate directly with each other and do not employ an access point. The term client station or mobile station may not necessarily mean that a wireless network device is actually mobile. For example, a desktop computer that is not mobile may incorporate a wireless network device and operate as a mobile station or client station. A wireless network that operates in the infrastructure mode includes an access point (AP) and at least one client station that communicates with the AP.

Referring now to FIG. **1**, a first wireless network **10** is illustrated in an infrastructure mode. The first wireless network **10** includes one or more client stations **12** and one or more access points (AP) **14**. The client station **12** and the AP **14** transmit and receive wireless signals **16**. The AP **14** is a node in a network **18**. The network **18** may be a local area network (LAN), a wide area network (WAN), or another network configuration. The network **18** may include other nodes such as a server **20** and may be connected to a distributed communications system **22** such as the Internet.

Referring now to FIG. **2**, a second wireless network **24** operates in an ad-hoc mode. The second wireless network **24** includes multiple client stations **26-1**, **26-2**, and **26-3** that transmit and receive wireless signals **28**. The client stations **26-1**, **26-2**, and **26-3** collectively form a LAN and communicate directly with each other.

To improve range, signal quality, and bandwidth, some wireless network devices may employ multiple transmit and receive antennas. The network devices may steer signals launched from an array of antennas to improve performance.

SUMMARY

A network device comprises a calibration module that receives a first channel state information (CSI) matrix from a link partner, that determines CSI based on radio frequency (RF) signals transmitted from the link partner, and that generates a second CSI matrix that includes the CSI for the RF signals. The network device comprises a first steering module that determines a first steering matrix based on the first CSI matrix, a control module that adjusts beamforming weights based on the first steering matrix, and a second steering module that determines a second steering matrix based on the second CSI matrix and that transmits the second steering matrix to the link partner.

In another feature, the beamforming weights are adjusted to direct RF signals toward the link partner.

In another feature, the calibration module transmits a set of training signals to the link partner. The first CSI matrix is based on the training signals. At least one of the training signals includes a frame that indicates whether the network device is capable of generating the second steering matrix.

In another feature, at least one of the RF signals includes a frame that indicates whether the link partner is capable of directing the RF signals toward the network device based on the second steering matrix.

In another feature, the network device of claim **1** further comprises a set of RF transceivers that transmit and receive RF signals and a beamforming module that directs the RF transceivers to transmit toward the link partner based on the first steering matrix.

In another feature, an access point (AP) comprises the network device.

In another feature, a wireless network comprises the network device and further comprises the link partner, wherein the link partner comprises a set of RF transceivers that transmit and receive RF signals, and a beamforming module that directs the RF transceivers to transmit toward the network device based on the second steering matrix.

In another feature, a wireless network comprises the AP and further comprises the link partner, wherein the link partner comprises a set of RF transceivers that transmit and receive RF signals and a beamforming module that directs the RF transceivers to transmit toward the network device based on the second steering matrix.

In another feature, the link partner further comprises a secondary calibration module that generates the first CSI matrix. The link partner further comprises a secondary steering module that generates a secondary steering matrix based on the CSI and a secondary control module that directs the beamforming module to adjust beamforming weights, wherein the beamforming weights direct the RF signals toward the network device.

In still other features, a network device comprises a calibration module that determines channel state information (CSI) based on radio frequency (RF) signals transmitted from a link partner, that generates a CSI matrix that includes the CSI for the RF signals, that transmits the CSI matrix to the link partner, and that receives a steering matrix from the link partner. The network device comprises a control module that adjusts beamforming weights based on the steering matrix.

In another feature, the calibration module transmits a set of training signals to the link partner. The steering matrix is based on the training signals. At least one of the training signals includes a frame that indicates whether the network device is capable of adjusting the beamforming weights based on the steering matrix.

In another feature, at least one of the RF signals includes a frame that indicates whether the link partner is capable of generating the steering matrix.

In another feature, the network device further comprises a set of RF transceivers that transmit and receive RF signals and a beamforming module that directs the RF signals toward the link partner.

In another feature, a wireless network comprises the network device and further comprises a link partner, wherein the link partner comprises a set of RF transceivers that transmit and receive RF signals and a beamforming module that

directs the RF transceivers to transmit toward the network device based on the CSI matrix.

In another feature, the link partner includes an access point.

In another feature, the link partner further comprises a second calibration module that receives the CSI matrix, that determines a second CSI based on the RF signals, and that generates a second CSI matrix that includes the second CSI for each of the RF signals. The link partner further comprises a first steering module that determines the steering matrix based on the second CSI matrix, a second steering module that determines a second steering matrix based on the CSI matrix, and a second control module that adjusts a second set of beamforming weights based on the second steering matrix, wherein the RF signals are directed toward the network device when the second set of weights are adjusted.

In another feature, the network device further comprises a steering module that generates a second steering matrix based on a second CSI matrix received from the link partner.

In still other features, a method comprises receiving a first channel state information (CSI) matrix from a link partner, determining CSI based on radio frequency (RF) signals transmitted from the link partner, generating a second CSI matrix that includes the CSI for the RF signals, determining a first steering matrix based on the first CSI matrix, adjusting beamforming weights based on the first steering matrix, determining a second steering matrix based on the second CSI matrix, and transmitting the second steering matrix to the link partner.

In another feature, the method further comprises adjusting the beamforming weights to direct RF signals toward the link partner.

In another feature, the method further comprises transmitting a set of training signals to the link partner. The method further comprises generating the first CSI matrix based on the training signals. The method further comprises including a frame in at least one of the training signals to indicate ability to generate the second steering matrix.

In another feature, the method further comprises including a frame in at least one of the RF signals to indicate whether the link partner can direct the RF signals based on the second steering matrix.

In another feature, the method further comprises transmitting and receiving RF signals and directing transmission and reception of the RF signals toward the link partner based on the first steering matrix.

In another feature, the method further comprises transmitting and receiving RF signals at the link partner and directing transmission and reception of the RF signals at the link partner based on the second steering matrix.

In another feature, the method further comprises generating the first CSI matrix.

In another feature, the method further comprising generating a secondary steering matrix based on the CSI and adjusting beamforming weights, wherein the beamforming weights direct the RF signals.

In still other features, a method comprises determining channel state information (CSI) based on radio frequency (RF) signals transmitted from a link partner, generating a CSI matrix that includes the CSI for the RF signals, transmitting the CSI matrix to the link partner, receiving a steering matrix from the link partner, and adjusting beamforming weights based on the steering matrix.

In another feature, the method further comprises transmitting a set of training signals to the link partner. The method further comprises generating the steering matrix based on the training signals. The method further comprises including a frame in at least one of the training signals to indicate ability to adjust beamforming weights based on the steering matrix.

In another feature, the method further comprises including a frame in at least one of the RF signals to indicate whether the link partner can generate the steering matrix.

In another feature, the method further comprises that transmitting and receiving RF signals and directing transmission and reception of the RF signals toward the link partner.

In another feature, the method further comprises transmitting and receiving RF signals at the link partner and directing transmission and reception of the RF signals at the link partner based on the CSI matrix.

In another feature, the method further comprises receiving the CSI matrix, determining a second CSI based on the RF signals, generating a second CSI matrix that includes the second CSI for each of the RF signals, determining the steering matrix based on the second CSI matrix, determining a second steering matrix based on the CSI matrix, adjusting a second set of beamforming weights based on the second steering matrix, and directing the RF signals when the second set of weights are adjusted.

In another feature, the method further comprises generating a second steering matrix based on a second CSI matrix received from the link partner.

In still other features, a network device comprises calibration means for receiving a first channel state information (CSI) matrix from a link partner, determining CSI based on radio frequency (RF) signals transmitted from the link partner, and generating a second CSI matrix that includes the CSI for the RF signals. The network device further comprises first steering means for determining a first steering matrix based on the first CSI matrix, control means for adjusting beamforming weights based on the first steering matrix, and second steering means for determining a second steering matrix based on the second CSI matrix and that transmits the second steering matrix to the link partner.

In another feature, the beamforming weights are adjusted to direct RF signals toward the link partner.

In another feature, the calibration means transmits a set of training signals to the link partner. The first CSI matrix is based on the training signals. At least one of the training signals includes a frame that indicates whether the network device is capable of generating the second steering matrix.

In another feature, at least one of the RF signals includes a frame that indicates whether the link partner is capable of directing the RF signals toward the network device based on the second steering matrix.

In another feature, the network device further comprises RF transceiver means for transmitting and receiving RF signals and beamforming means for directing the RF transceiver means to transmit toward the link partner based on the first steering matrix.

In another feature, an access point (AP) comprises the network device.

In another feature, a wireless network comprises the network device and further comprises the link partner, wherein the link partner comprises RF transceiver means for transmitting and receiving RF signals and beamforming means for directing the RF transceiver means to transmit toward the network device based on the second steering matrix.

In another feature, a wireless network comprises the AP and further comprises the link partner, wherein the link partner comprises RF transceiver means for transmitting and receiving RF signals and beamforming means for directing the RF transceiver means to transmit toward the network device based on the second steering matrix.

In another feature, the link partner further comprises secondary calibration means for generating the first CSI matrix.

In another feature, the link partner further comprises secondary steering means for generating a secondary steering matrix based on the CSI and secondary control means for directing the beamforming means to adjust beamforming weights, wherein the beamforming weights direct the RF signals toward the network device.

In still other features, a network device comprises calibration means for determining channel state information (CSI) based on radio frequency (RF) signals transmitted from a link partner, generating a CSI matrix that includes the CSI for the RF signals, transmitting the CSI matrix to the link partner, and receiving a steering matrix from the link partner. The network device further comprises control means for adjusting beamforming weights based on the steering matrix.

In another feature, the calibration means transmits a set of training signals to the link partner.

In another feature, the steering matrix is based on the training signals. At least one of the training signals includes a frame that indicates whether the network device is capable of adjusting the beamforming weights based on the steering matrix.

In another feature, at least one of the RF signals includes a frame that indicates whether the link partner is capable of generating the steering matrix.

In another feature, the network device further comprises RF transceiver means for transmitting and receiving RF signals and beamforming means for directing the RF signals toward the link partner.

In another feature, a wireless network comprises the network device and further comprises a link partner, wherein the link partner comprises RF transceiver means for transmitting and receiving RF signals and beamforming means for directing the RF transceiver means to transmit toward the network device based on the CSI matrix.

In another feature, the link partner includes an access point.

In another feature, the link partner further comprises second calibration means for receiving the CSI matrix, determining a second CSI based on the RF signals, and generating a second CSI matrix that includes the second CSI for each of the RF signals. The link partner further comprises first steering means for determining the steering matrix based on the second CSI matrix, second steering means for determining a second steering matrix based on the CSI matrix, and second control means for adjusting a second set of beamforming weights based on the second steering matrix, wherein the RF signals are directed toward the network device when the second set of weights are adjusted.

In another feature, the network device further comprises a steering means for generating a second steering matrix based on a second CSI matrix received from the link partner.

In still other features, a computer program executed by a processor comprises receiving a first channel state information (CSI) matrix from a link partner, determining CSI based on radio frequency (RF) signals transmitted from the link partner, generating a second CSI matrix that includes the CSI for the RF signals, determining a first steering matrix based on the first CSI matrix, adjusting beamforming weights based on the first steering matrix, determining a second steering matrix based on the second CSI matrix, and transmitting the second steering matrix to the link partner.

In another feature, the computer program further comprises adjusting the beamforming weights to direct RF signals toward the link partner.

In another feature, the computer program further comprises transmitting a set of training signals to the link partner. The computer program further comprises generating the first CSI matrix based on the training signals. The computer program further comprises including a frame in at least one of the training signals to indicate ability to generate the second steering matrix.

In another feature, the computer program further comprises including a frame in at least one of the RF signals to indicate whether the link partner can direct the RF signals based on the second steering matrix.

In another feature, the computer program further comprises transmitting and receiving RF signals and directing transmission and reception of the RF signals toward the link partner based on the first steering matrix.

In another feature, the computer program further comprises transmitting and receiving RF signals at the link partner and directing transmission and reception of the RF signals at the link partner based on the second steering matrix.

In another feature, the computer program further comprises generating the first CSI matrix.

In another feature, the computer program further comprising generating a secondary steering matrix based on the CSI and adjusting beamforming weights, wherein the beamforming weights direct the RF signals.

In still other features, a computer program executed by a processor comprises determining channel state information (CSI) based on radio frequency (RF) signals transmitted from a link partner, generating a CSI matrix that includes the CSI for the RF signals, transmitting the CSI matrix to the link partner, receiving a steering matrix from the link partner, and adjusting beamforming weights based on the steering matrix.

In another feature, the computer program further comprises transmitting a set of training signals to the link partner. The computer program further comprises generating the steering matrix based on the training signals. The computer program further comprises including a frame in at least one of the training signals to indicate ability to adjust beamforming weights based on the steering matrix.

In another feature, the computer program further comprises including a frame in at least one of the RF signals to indicate whether the link partner can generate the steering matrix.

In another feature, the computer program further comprises that transmitting and receiving RF signals and directing transmission and reception of the RF signals toward the link partner.

In another feature, the computer program further comprises transmitting and receiving RF signals at the link partner and directing transmission and reception of the RF signals at the link partner based on the CSI matrix.

In another feature, the computer program further comprises receiving the CSI matrix, determining a second CSI based on the RF signals, generating a second CSI matrix that includes the second CSI for each of the RF signals, determining the steering matrix based on the second CSI matrix, determining a second steering matrix based on the CSI matrix, adjusting a second set of beamforming weights based on the second steering matrix, and directing the RF signals when the second set of weights are adjusted.

In another feature, the computer program further comprises generating a second steering matrix based on a second CSI matrix received from the link partner.

In still other features, the systems and methods described above are implemented by a computer program executed by one or more processors. The computer program can reside on a computer readable medium such as but not limited to memory, non-volatile data storage and/or other suitable tangible storage mediums.

Further areas of applicability of the present disclosure will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the disclosure, are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure will become more fully understood from the detailed description and the accompanying drawings, wherein:

FIG. **1** is functional block diagram of a wireless network operating in an infrastructure mode;

FIG. **2** is a function block diagram of a wireless network operating in an ad-hoc mode;

FIG. **3** is a functional block diagram of an exemplary multiple input multiple output (MIMO) wireless network;

FIG. **4** is a flowchart illustrating exemplary steps that may be implemented to adjust beamforming weights associated with a network device;

FIG. **5** is a flowchart illustrating exemplary steps that may be implemented to provide channel state information (CSI) feedback to the network device;

FIG. **6** is a functional block diagram of an exemplary multiple input multiple output (MIMO) wireless network that has primary and secondary network devices;

FIG. **7** is a flowchart illustrating exemplary steps that may be implemented by the primary network device in determining a steering matrix for the secondary network device;

FIG. **8** is a flowchart illustrating exemplary steps that may be implemented by the secondary network device in determining a steering matrix;

FIG. **9**A is a functional block diagram of a high definition television;

FIG. **9**B is a functional block diagram of a vehicle control system;

FIG. **9**C is a functional block diagram of a cellular phone;

FIG. **9**D is a functional block diagram of a set top box; and

FIG. **9**E is a functional block diagram of a media player.

DETAILED DESCRIPTION

The following description is merely exemplary in nature and is in no way intended to limit the disclosure, its application, or uses. For purposes of clarity, the same reference numbers will be used in the drawings to identify similar elements. As used herein, the term module, circuit and/or device refers to an Application Specific Integrated Circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group) and memory that execute one or more software or firmware programs, a combinational logic circuit, and/or other suitable components that provide the described functionality. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A or B or C), using a non-exclusive logical or. It should be understood that steps within a method may be executed in different order without altering the principles of the present disclosure.

Referring now to FIG. **3**, an exemplary multiple input multiple output (MIMO) network as described in IEEE 802.11(n) draft specification (as proposed in Enhanced Wireless Consortium, HT PHY Specification v1.28, Jan. 2, 2006 and Enhanced Wireless Consortium, HT MAC Specification v1.28, Dec. 23, 2005), which is incorporated by reference in its entirety, is depicted at **100**. A first device **102**, such as an access point (AP) or a client station, may communicate with a second device **104**, such as an AP or client station. When the first and second devices **102**, **104** communicate with each other they may be generally referred to as link partners.

The first and second devices **102** and **104** include physical layer (PHY) modules **111** and **118** and media access control (MAC) modules **123** and **129**, respectively. The first device **102** device may include a first set of antennas **106-1**, **106-2**, . . . , and **106**-*n* and the second device **104** may include a second set of antennas **108-1**, . . . , and **108**-*m*. The first device **102** may parse a single frame into multiple spatial streams and then simultaneously transmit multiple RF signals **110** to the second device **104**. The second device **104** may receive the multiple RF signals **110** and reassemble them into a single frame. Similarly, the second device **104** may simultaneously transmit multiple RF signals **110** to the first device **102**, which may reassemble them into a single frame.

To increase transmission rates, the first **102** and second device **104** may utilize beamforming. Beamforming is a method to increase channel capacity, and consequently transmission rates, by increasing signal to noise ratio (SNR) of an RF signal. Beamforming combines RF signals from a set of small non-directional antennas to simulate a directional antenna. The combined RF signals can be pointed (or steered) in a particular direction to increase signal strength, which increases SNR. When receiving a signal, beamforming can increase RF signal gain in the direction of wanted signals and decrease the gain for non-intended users. When transmitting a signal, beamforming can increase the gain in the direction that the signal is to be sent, which may be accomplished by creating beams and nulls in the radiation pattern.

The PHY module **111** includes a beamforming module **112** with a first set of adjustable weights **114-1**, **114-2**, . . . , and **114**-*n*. Each weight **114-1**, **114-2**, . . . , and **114**-*n* may be adjusted to manipulate signals received from a respective transceiver **116-1**, **116-2**, . . . , and **116**-*n* to collectively steer signals launched from the antennas **106** in a particular direction. The weights **114-1**, **114-2**, . . . , and **114**-*n* are typically complex weights that include an amplitude and a phase shift portion. However, other weight configurations may be possible.

Similarly, the PHY module **118** includes a beamforming module **119** with a second set of adjustable weights **120-1**, . . . , and **120**-*m*. Each weight **120-1**, . . . , and **120**-*m* may be adjusted to manipulate signals received from a respective transceiver **122-1**, . . . , and **122**-*m* to collectively steer signals launched from the antennas **108** in a particular direction. The weights **120-1**, . . . , and **120**-*n* are typically complex weights that include an amplitude and a phase shift portion, however other weight configurations may be possible. To adjust the weights **114** and **120**, the first and second devices **102**, **104** may use channel state information (CSI) feedback. The CSI feedback may include a signal to noise ratio for each RF signal **110**.

The MAC module **123** includes a control module **124**, a steering module **126**, and a calibration module **128**. The control module **124**, steering module **126**, and calibration module **128** may be implemented individually and/or combined into one or more modules. The MAC module **123** may communicate with the PHY module **111**. In some embodiments, the calibration module **128** may communicate with RF transceivers **116**, the steering module **126** may communicate with the calibration module **128** and the control module **124**, and the control module **124** may communicate with the beamforming module **112**.

The MAC module **129** includes a second control module **130**, a second steering module **132**, and a second calibration module **134**. The MAC module **129** may communicate with the PHY module **118**. In some embodiments, the second calibration module **134** may communicate with RF transceivers **122**, the second steering module **132** may communicate with the second calibration module **134** and the second control module **130**, and the second control module **130** may communicate with the beamforming module **119**.

The first device **102** may obtain CSI from the second device **104** and adjust the weights **114** based thereon. More specifically, the calibration module **128** may generate and transmit a set of training signals to the second device **104**. The second calibration module **134** may determine CSI of the training signals and then transmit a CSI matrix that includes CSI for each training signal to the first device **102**. When the first device **102** receives the CSI matrix, the steering module **126** may generate a steering matrix based on the CSI matrix. The control module **124** may adjust the weights **114** based on the steering matrix to direct the RF signals **110** toward the second device **104**.

In a similar manner, the second device **104** may obtain CSI from the first device **102** and adjust the second set of weights **120** based thereon. More specifically, the second calibration module **134** may generate and transmit a set of training signals to the first device **102**. The calibration module **128** of the first device **102** may determine CSI of the training signals and then transmit a CSI matrix that includes CSI for each training signal to the second device **104**. When the second device **104** receives the CSI matrix, the second steering module **132** may generate a steering matrix based on the CSI matrix. The second control module **130** may adjust the second set of weights **120** based on the steering matrix to direct the RF signals **110** toward the first device **102**.

Referring now to FIG. **4**, exemplary steps that may be implemented to adjust the first set of weights **114** are generally depicted at **200**. The process starts in step **202** when the first device **102** has data to transmit to the second device **104**. In step **204**, the calibration module **128** may generate and transmit training signals to the second device **104**. In step **206**, the calibration module **128** may receive a CSI matrix from the second device **104**. The steering module **126** may determine a steering matrix based on the CSI matrix in step **208**. Once the steering matrix has been determined, the control module **124** may adjust the first set of weights **114** based on the steering matrix in step **210**.

In step **212**, the calibration module **128** may determine whether the RF signals **110** are directed toward the second device **104**. To determine whether the RF signals **110** are directed toward the second device **104**, the calibration module **128** may send a second set of training signals and receive a second CSI matrix based thereon. If the RF signals **110** are directed toward the second device **104**, the process ends in step **214**. However, if the RF signals **110** are not directed toward the target device, the process may return to step **204**. Although the first set of weights **114** are adjusted in this example, skilled artisans will recognize that the second set of weights **120** may be adjusted in a similar manner.

Referring now to FIG. **5**, exemplary steps taken to provide CSI feedback are generally depicted at **250**. The process begins in step **252** when the first device **102** has data to transmit to the second device **104**. In step **254**, the second calibration module **134** may receive training signals from the first device **102**. In step **256**, CSI of the training signals may be determined and a CSI matrix may be generated based thereon. In step **258**, the second calibration module **134** may transmit the CSI matrix to the first device **102**. The second calibration module **134** may determine if additional training signals are received from the first device **102** in step **260**. If the second device **104** does not receive additional training signals, the process may end in step **262**. If the second device **104** does receive additional training signals, the process may return to step **256**. Although the second device **104** is providing CSI feedback to the first device **102**, skilled artisans will recognize that the first device **102** may provide feedback to the second device **104** in a similar manner.

Referring now to FIG. **6**, some MIMO networks **300** may be configured to have a primary device **302**, such as an AP or a master client station, and a secondary device **304**, such as a client station or a slave client station that communicate with each other as link partners. The primary device **302** may capable of processing more data than the secondary device **304**. Therefore, the primary device **302** may determine a steering matrix for the secondary device **304** when the devices **302**, **304** are compatible. The devices **302**, **304** are compatible when the primary device **302** is capable of determining a steering matrix for the secondary device **304**, and the secondary device **304** is capable of adjusting the weights **120** based on the steering matrix. Since the secondary device **304** does not have to determine a steering matrix, the secondary device **304** may consume less power, which is advantageous for battery powered devices.

The primary device **302** device may include a set of primary antennas **306-1**, **306-2**, . . . , and **306-*n*** and the secondary device **304** may include a set of secondary antennas **308-1**, . . . , and **308-*m***. The primary device **302** may parse a single frame into multiple spatial streams and then simultaneously transmit multiple RF signals **310** to the secondary device **304**. The secondary device **304** may receive the multiple RF signals **310** and reassemble them into a single frame. Similarly, the secondary device **304** may simultaneously transmit multiple RF signals **310** to the primary device **302**, which may then receive and reassemble the RF signals **310** into a single frame.

The primary device **302** may include a PHY module **311** that includes a primary beamforming module **312** with an adjustable set of primary weights **314-1**, **314-2**, . . . , and **314-*n***. Each primary weight **314-1**, **314-2**, . . . , and **314-*n*** may be adjusted to manipulate signals received from a respective primary transceiver **316-1**, **316-2**, . . . , and **316-*n*** to collectively steer signals launched from the primary antennas **306** in a particular direction. The primary weights **314-1**, **314-2**, . . . , and **314-*n*** are typically complex weights that include an amplitude and a phase shift portion, however other weight configurations may be possible.

Similarly, the secondary device **304** may include a PHY module **318** that includes a secondary beamforming module **319** with an adjustable set of secondary weights **320-1**, . . . , and **320-*m***. Each secondary weight **320-1**, . . . , and **320-*m*** may be adjusted to manipulate signals received from a respective secondary transceiver **322-1**, . . . , and **322-*m*** to collectively steer signals launched from the secondary antennas **308** in a particular direction. The secondary weights **320-1**, . . . , and **320-*n*** are typically complex weights that include an amplitude and a phase shift portion, however other weight configurations may be possible. To adjust the primary and secondary weights **114** and **120**, the primary and secondary devices **302**, **304** may use channel state information (CSI) feedback. The CSI feedback may include a signal to noise ratio for each RF signal **310**.

The primary device **302** may include a MAC module **323** that includes a primary control module **324**, a first steering module **326**, a primary calibration module **328**, and a second steering module **329**. The MAC module **323** may communicate with the PHY module **311**. In some embodiments, the primary calibration module **328** may communicate with the RF transceivers **316** and the second steering module **329**, the first steering module **326** may communicate with the primary calibration module **328** and the primary control module **324**, and the primary control module **324** may communicate with the primary beamforming module **312**.

The secondary device **304** may include a MAC module **330** that may include a secondary control module **331**, a secondary steering module **332**, and a secondary calibration module **334**. The MAC module **330** may communicate with the PHY module **318**. In some embodiments, the secondary calibration module **334** may communicate with the RF transceivers **322** and the secondary control module **331**, the secondary steering module **332** may communicate with the secondary calibration module **334** and the secondary control module **331**, and the secondary control module **331** may communicate with the secondary beamforming module **319**.

The primary device **302** may obtain CSI from the secondary device **304** and adjust the primary weights **314** based thereon. More specifically, the primary calibration module **328** may generate and transmit a set of training signals to the second device **304**. The training signals may include a management action frame that indicates whether the primary device **302** is capable of determining a steering matrix for the secondary device **304** based on a CSI matrix. In some embodiments, the secondary device **304** may not be capable of determining a steering matrix based on a CSI matrix when in a power save mode. In other embodiments, the secondary device **304** may not include the secondary steering module **332** and therefore would not be capable of determining a steering matrix based on a CSI matrix.

The calibration module **334** may determine CSI of the training signals and then transmit a CSI matrix that includes CSI for each training signal to the primary device **302**. When the primary device **302** receives the CSI matrix, the first steering module **326** may generate a steering matrix based on the CSI matrix. The primary control module **324** may adjust the primary weights **314** based on the steering matrix to direct the RF signals **110** toward the secondary device **304**.

The secondary device **304** may obtain data from the primary device **302** and adjust the secondary weights **320** based thereon. More specifically, the secondary calibration module **334** may generate and transmit a set of training signals to the first device **102**. The training signals may include a management action frame that indicates whether the secondary device **304** is capable of adjusting the secondary weights **320** based on a steering matrix received from the primary device **302**. As previously mentioned, in some embodiments the secondary device may not be capable of determining a steering matrix based on a CSI matrix when in a power save mode. In other embodiments, the secondary device **304** may not include the secondary steering module **332** and therefore would not be capable of determining a steering matrix based on a CSI matrix.

If the secondary device **304** is not capable of adjusting the weights **320** based on a steering matrix received from the primary device **302**, the primary calibration module **328** may determine CSI of the training signals and then transmit a CSI matrix that includes CSI for each training signal to the secondary device **304**. When the secondary device **304** receives the CSI matrix, the secondary steering module **332** may generate a steering matrix based on the CSI matrix. The secondary control module **331** may adjust the secondary weights **320** based on the steering matrix to direct the RF signals **310** toward the primary device **302**.

However, if the secondary device **304** is capable of adjusting the weights **320** based on a steering matrix received from the primary device **302**, the primary calibration module **328** may determine CSI of the training signals. The second steering module **329** of the primary device **302** may then determine a steering matrix for the secondary device **304** based on the CSI matrix. The primary calibration module **328** may then transmit the steering matrix determined by the second steering module **329** to the secondary device **304**. When the secondary device **304** receives the steering matrix, the secondary control module **331** may adjust the secondary weights **320** based on the received steering matrix to direct the RF signals **310** toward the primary device **302**.

Referring now to FIG. **7**, the primary device **302** may implement steps generally identified at **400** to assist the secondary device **304** in determining a steering matrix for the secondary device **304**. The process begins in step **402** when the secondary device **304** has data to transmit to the primary device **302**. In step **404**, the primary device **302** receives training signals from the secondary device **304**. As previously mentioned, the training signals may include a management action frame that indicates whether the secondary device **304** is capable adjusting the secondary weights **320** based on a steering matrix generated by the primary device **302**.

The primary calibration module **328** may determine CSI of the training signals in step **406**. In step **408**, the primary calibration module **328** may inspect the management information frame and determine whether the secondary device **304** is capable of receiving a steering matrix from the primary device **302** and directing the RF signals **310** toward the primary device **302** based thereon. If the secondary device **304** is not capable of receiving a steering matrix from the primary device **302**, the primary calibration device **328** generates a CSI matrix in step **410**. The CSI matrix may be transmitted to the secondary device **304** in step **412** and the process may end in step **414**.

However, if the secondary device **304** is capable, the secondary steering module **323** of the primary device **302** may determine a steering matrix for the secondary device in step **416**. In step **418**, the primary calibration module **328** may transmit the steering matrix to the secondary device and the process may end in step **414**.

Referring now to FIG. **8**, the secondary device **304** may implement steps generally identified at **450** in determining a steering matrix. The process begins in step **452** when the secondary device **304** has data to transmit to the primary device **302**. In step **454**, the secondary device **304** transmits training signals to the primary device **302**. As previously mentioned, the training signals may include a management action frame that indicates whether the secondary device **304** is capable adjusting the weights **320** based on a steering matrix generated by the primary device **302**.

The secondary calibration module **334** may receive a matrix based on the training signals from the primary device **302** in step **456**. In step **458**, the secondary calibration module **334** may determine whether the matrix received from the primary device **302** is a steering matrix. If the matrix is a steering matrix, the secondary control module **331** may adjust the weights **320** based on the steering matrix in step **460** and the process may end in step **462**.

However, if the matrix received from the primary device **302** is not a steering matrix, the secondary steering module **332** may determine a steering matrix based on the matrix received from the primary device **302** in step **464**. The secondary control module **331** may then adjust the secondary weights **320** based on the steering matrix in step **460** and the process may end in step **462**.

Referring now to FIGS. **9**A-**9**E, various exemplary implementations of the systems and methods of present disclosure are shown. Referring now to FIG. **9**A, the systems and methods of present disclosure can be implemented in a WLAN interface **529** of a high definition television (HDTV) **520**. The

HDTV **520** receives HDTV input signals in either a wired or wireless format and generates HDTV output signals for a display **526**. In some implementations, signal processing circuit and/or control circuit **522** and/or other circuits (not shown) of the HDTV **520** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other type of HDTV processing that may be required.

The HDTV **520** may communicate with mass data storage **527** that stores data in a nonvolatile manner such as optical and/or magnetic storage devices. The HDTV **520** may be connected to memory **528** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. The HDTV **520** also may include a power supply **523**.

Referring now to FIG. **9**B, the systems and methods of present disclosure may be implemented in a WLAN interface **548** of a vehicle **530**. A powertrain control system **532** receives inputs from one or more sensors such as temperature sensors, pressure sensors, rotational sensors, airflow sensors and/or any other suitable sensors and/or that generates one or more output control signals such as engine operating parameters, transmission operating parameters, and/or other control signals.

A control system **540** may likewise receive signals from input sensors **542** and/or output control signals to one or more output devices **544**. In some implementations, the control system **540** may be part of an anti-lock braking system (ABS), a navigation system, a telematics system, a vehicle telematics system, a lane departure system, an adaptive cruise control system, a vehicle entertainment system such as a stereo, DVD, compact disc and the like. Still other implementations are contemplated.

The powertrain control system **532** may communicate with mass data storage **546** that stores data in a nonvolatile manner. The mass data storage **546** may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. The powertrain control system **532** may be connected to memory **547** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. The powertrain control system **532** also may support connections with a WLAN via WLAN interface **548**. Vehicle **530** may also include a power supply **533**.

Referring now to FIG. **9**C, the systems and methods of present disclosure can be implemented in a WLAN interface **568** of a cellular phone **550** that may include a cellular antenna **551**. In some implementations, the cellular phone **550** includes a microphone **556**, an audio output **558** such as a speaker and/or audio output jack, a display **560** and/or an input device **562** such as a keypad, pointing device, voice actuation and/or other input device. The signal processing and/or control circuits **552** and/or other circuits (not shown) in the cellular phone **550** may process data, perform coding and/or encryption, perform calculations, format data and/or perform other cellular phone functions.

The cellular phone **550** may communicate with mass data storage **564** that stores data in a nonvolatile manner such as optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. The cellular phone **550** may be connected to memory **566** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. The cellular phone **550** also may support connections with a WLAN via WLAN interface **968**. Cellular phone **550** may also include a power supply **553**.

Referring now to FIG. **9**D, the systems and methods of present disclosure can be implemented in a WLAN interface **596** of a set top box **580**. The set top box **580** receives signals from a source such as a broadband source and outputs standard and/or high definition audio/video signals suitable for a display **588** such as a television and/or monitor and/or other video and/or audio output devices. The signal processing and/or control circuits **584** and/or other circuits (not shown) of the set top box **580** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other set top box function.

The set top box **580** may communicate with mass data storage **590** that stores data in a nonvolatile manner. The mass data storage **590** may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. The set top box **580** may be connected to memory **594** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. The set top box **580** also may support connections with a WLAN via WLAN interface **596**. Set top box **580** may also include a power supply **583**.

Referring now to FIG. **9**E, the systems and methods of present disclosure can be implemented in a WLAN interface **1016** of a media player **600**. In some implementations, the media player **1000** includes a display **1007** and/or a user input **1008** such as a keypad, touchpad and the like. In some implementations, the media player **1000** may employ a graphical user interface (GUI) that typically employs menus, drop down menus, icons and/or a point-and-click interface via the display **1007** and/or user input **1008**. The media player **1000** further includes an audio output **1009** such as a speaker and/or audio output jack. The signal processing and/or control circuits **1004** and/or other circuits (not shown) of the media player **1000** may process data, perform coding and/or encryption, perform calculations, format data and/or perform any other media player function.

The media player **1000** may communicate with mass data storage **1010** that stores data such as compressed audio and/or video content in a nonvolatile manner. In some implementations, the compressed audio files include files that are compliant with MP3 format or other suitable compressed audio and/or video formats. The mass data storage may include optical and/or magnetic storage devices for example hard disk drives HDD and/or DVDs. The media player **1000** may be connected to memory **514** such as RAM, ROM, low latency nonvolatile memory such as flash memory and/or other suitable electronic data storage. The media player **1000** also may support connections with a WLAN via WLAN interface **1016**. Media player **1000** may also include a power supply **1013**. Still other implementations in addition to those described above are contemplated.

Those skilled in the art can now appreciate from the foregoing description that the broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, the specification and the following claims.

What is claimed is:

1. A first network device comprising:

a calibration module configured to receive a training signal from a second network device, the training signal indicating that the second network device is capable of adjusting beamforming weights associated with the second network device based on a steering matrix received from the first network device; and

a steering module configured to

determine a first steering matrix for the second network device based on the training signal; and

transmit the first steering matrix to the second network device for adjustment of the beamforming weights associated with the second network device.

2. The first network device of claim **1**, wherein the beamforming weights associated with the second network device direct radio frequency (RF) signals toward the first network device.

3. The first network device of claim **1**, wherein the second network device is a link partner of the first network device.

4. The first network device of claim **1**, wherein:

the training signal comprises a management frame; and

the management frame provides the indication that the second network device is capable of adjusting beamforming weights associated with the second network device based on a steering matrix received from the first network device.

5. The first network device of claim **1**, wherein the first network device comprises an access point.

6. A wireless network comprising:

the first network device of claim **1**; and

the second network device.

7. The wireless network of claim **6**, wherein the wireless network comprises a multiple input multiple output (MIMO) network.

8. The wireless network of claim **7**, wherein the multiple input multiple output (MIMO) network is compliant with the IEEE 802.11(n) specification.

9. A method comprising:

receiving, at a first network device, a training signal from a second network device, wherein the training signal indicates that the second network device is capable of adjusting beamforming weights associated with the second network device based on a steering matrix received from the first network device; and

the first network device determining a first steering matrix for the second network device based on the training signal; and

transmitting, from the first network device, the first steering matrix to the second network device for adjustment of the beamforming weights associated with the second network device.

10. The method of claim **9**, wherein the beamforming weights associated with the second network device direct radio frequency (RF) signals toward the first network device.

11. The method of claim **9**, wherein the second network device is a link partner of the first network device.

12. The method of claim **9**, wherein:

the training signal comprises a management frame; and

the management frame provides the indication that the second network device is capable of adjusting beamforming weights associated with the second network device based on a steering matrix received from the first network device.

13. The method of claim **9**, wherein the first network device comprises an access point.

* * * * *